Design Opportunities and Challenges in the Development of Vertical Lift Planetary Aerial Vehicles

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Abstract

The next few years promise a unique convergence of NASA aeronautics and space programs. NASA planetary science missions are becoming increasingly more sophisticated. This will ultimately culminate, in part, in the development of planetary aerial vehicles (PAVs). Early work in this area has principally focused on conceptual design of fixed-wing aircraft configurations for Mars exploration. However, autonomous vertical lift vehicles hold considerable potential for supporting planetary science and exploration missions. This paper discusses in a general sense the technical opportunities and challenges in developing autonomous vertical lift PAVs. Through this discussion a vision for using PAVs in planetary exploration is presented.

Introduction

Manned and robotic exploration of the Solar system planets would be greatly enhanced through the development and use of robotic aerial vehicles. Since the 1970's a number of Mars (fixed-wing) Airplane concepts have been proposed for Mars exploration.

The Army/NASA Rotorcraft Division -- in collaboration with the Center for Mars Exploration -- at NASA Ames has been performing initial conceptual design studies over the past year of a Martian autonomous rotorcraft for planetary exploration and science missions (fig. 1). Initial results have been quite promising. As a result of this early work, the authors have generalized their thoughts regarding the utility of rotorcraft, VTOL vehicles, and hybrid airships for Mars exploration and planetary science missions as a whole.

Presented at the American Helicopter Society International Vertical Lift Aircraft Design Specialist's Meeting, San Francisco, CA, January 19-21, 2000.

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14. ABSTRACT
The next few years promise a unique convergence of NASA aeronautics and space programs. NASA planetary science missions are becoming increasingly more sophisticated. This will ultimately culminate, in part, in the development of planetary aerial vehicles (PAVs). Early work in this area has principally focused on conceptual design of fixed-wing aircraft configurations for Mars exploration. However, autonomous vertical lift vehicles hold considerable potential for supporting planetary science and exploration missions. This paper discusses in a general sense the technical opportunities and challenges in developing autonomous vertical lift PAVs. Through this discussion a vision for using PAVs in planetary exploration is presented.

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Why vertical lift vehicles for planetary exploration? For the same reason that these vehicles are such flexible aerial platforms for terrestrial exploration and transportation: the ability to hover and fly at low-speeds and to take-off and land at unprepared remote sites. Further, autonomous vertical lift planetary aerial vehicles (PAVs) would have the following specific advantages/capabilities for planetary exploration:

- Hover and low-speed flight capability would enable detailed and panoramic survey of remote sites;
- Vertical lift configurations would enable remote-site sample return to lander platforms, and/or precision placement of scientific probes;
- Soft landing capability for vehicle reuse (i.e. lander refueling and multiple sorties) and remote-site monitoring;
- Hover/soft landing are good fail-safe 'hold' modes for autonomous operation of PAVs;
- Vertical lift PAVs would provide greater range and speed than a surface rover while performing detailed surveys;
- Vertical lift PAVs would provide greater resolution of surface details, or observation of atmospheric phenomena, than an orbiter;
- Vertical lift vehicles would provide greater access to hazardous terrain than a lander or rover.

Further, even if a planetary aerial vehicle is not a vertical lift aircraft or rotorcraft, there are several rotary-wing technologies that will nonetheless have a profound influence on PAV development. These technologies include: high-efficiency propeller or proprotor design; precision guidance, navigation and control at low altitudes and near-terrain obstacles; adaptive (inner-loop) flight control; autonomous systems work based on vertical lift vehicle applications; high-frequency open- and closed-loop smart structures/actuators.

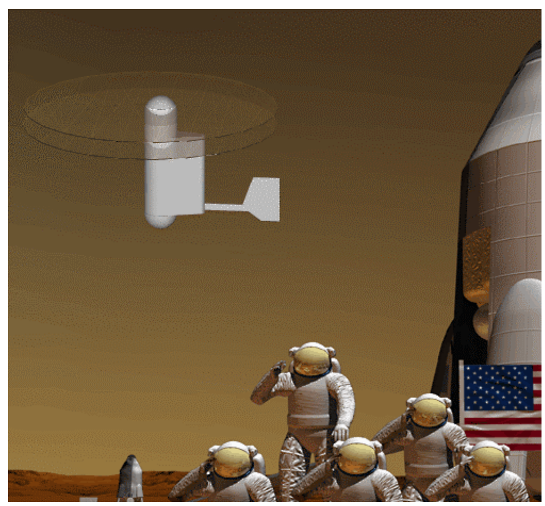

Figure 1 – Vertical Lift Planetary Aerial Vehicles as 'Astronaut Agents'

The objective of this paper is to inspire the vertical flight research community to consider and to embrace the concept of vertical lift planetary aerial vehicles and to participate in their ultimate development and use.

State of the Art in Planetary Science

Over the past forty years planetary science has made incredible advances by means of robotic missions carried out by spacecraft from our planet. Fly-by probes, orbiters, landers, hard-probes/penetrators, rovers, and aerostats have been launched, successfully completed their missions, and provided us invaluable data to expand our understanding of the solar system (fig. 2). Today, planetary science is poised to make further advances using robotic planetary aerial vehicles to conduct scientific investigations.

The development or evolution of planetary aerial vehicles will likely parallel the evolution of terrestrial flying vehicles: first will come balloons, followed by airships and/or fixed-wing aircraft, and finally rotary-wing or vertical lift vehicles. Balloons, or aerostats, have already been flown in Venus' upper atmosphere (jointly by the Soviet Union and France) on the Vega 1 and 2 missions in December 1984. Soon other types of PAVs will be developed, launched, and used to conduct planetary science missions.

The development of PAVs will pose new and exciting challenges for aeronauticalengineers.

Opportunities

As noted earlier, work is being pursued at the Ames Research Center's Army/NASA Rotorcraft Division on a Martian autonomous rotorcraft. Why not, though, as a next step, a Venusian VTOL? Or a Jovian flyer? Or, even, a Titan rotary-wing aircraft? Application of vertical lift and rotary-wing technologies to the development of planetary aerial vehicles would be extremely beneficial to the United States' long-term planetary exploration effort.

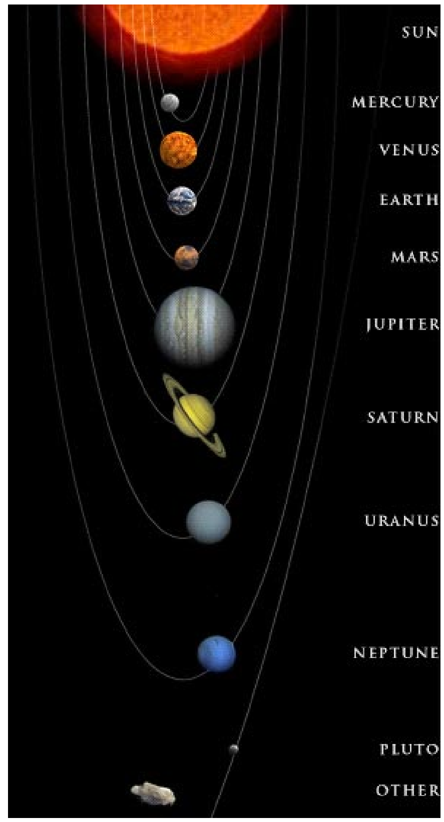

Fig. 2 – Our Solar System

This paper poses -- and makes an initial start in addressing -- the question of the feasibility of vertical lift PAVs, as well as the more general question of the applicability of rotary-wing technologies to planetary science and exploration. Table 1 is a summary of the key surface atmospheric properties for various planets in our solar system. This table has been divided into three parts: a description of terrestrial type planets and moons; outer, or gas-giant, planets;

planets and moons with tenuous, or nonexistent, atmospheres. Later in the paper this information will be used to examine the general aerodynamic attributes of vertical lift, and other, planetary vehicles.

Table 1 – Summary of Planetary Descriptions (Ref. 1)

	Mean Radius (km)	Gravity[1] (m/s^2)	Mean Surface Atmos. Temp. (° K)	Mean Surface Atmos. Pressure (Pa)	Mean Surface Atmos. Density (kg/m^3)	Atmos. Gases
Terrestrial Type Planets & Moons						
Venus	6052	8.87	735.3	9.21×10^6	64.79	CO_2 96% N_2 3.5%
Earth	6371	9.82	288.2	101,300	1.23	N_2 78% O_2 21%
Mars□	3390	3.71	214	636	1.55×10^{-2}	CO_2 95% N_2 2.7% Ar 1.6% O_2 0.1%
Titan (Saturn moon)	2575	1.354	94	149,526	5.55	N_2 65-98% Ar<25 % CH_4 2-10%
'Gas Giant' Planets♦						
Jupiter	69,200	25.0	165	100,000	0.173	H_2 86% He 13%
Saturn	57,400	10.6	135	100,000	0.196	H_2 96% He 3%
Uranus	25,250	8.94	76	100,000	0.365	H_2 83% He 15%
Neptune	24,500	11.2	72	100,000	0.438	H_2 80% He 19%
Planets & Moons with Tenuous Atmospheres						
Mercury	2438	3.70	100-700	$<10^{-12}$	--	--
Pluto	1151	0.645	40	$\sim 58 \times 10^{-6}$	--	N_2
The Moon	1737	1.62	120-390	--	--	--

[1] Mean values noted for planet radii and gravity to account for the oblateness of the planet.

□ Mars surface temperature, pressure, and density varies significantly spatially and temporally; surface temperature range of 140-300°K; surface pressure 636±240 Pa. Seasonal CO_2 sublimation and condensation at the polar caps (particularly at the southern polar cap) is the chief reason for the atmospheric pressure and density variations.

♦ All characteristics noted for the outer, gas-giant, planets in the Solar system are defined at effective (mean) planetary radii corresponding to 1bar atmospheric pressure.

Additional data related to key atmospheric properties can be found, for example, in Ref. 1-5. Despite the considerable amount of data related to planetary atmospheres, much more data can, and must, be discovered to enable the development and general application of PAVs.

In establishing the feasibility of vertical lift (and other) PAVs, it is not sufficient to merely question whether or not flight in extraterrestrial atmospheres is theoretically possible. It is also mandatory that one can clearly define general planetary science goals and opportunities that vertical lift PAV designs and missions can meet. Table 2 summarizes a partial list of planetary science goals/opportunities. Table 3 is a corresponding list of how vertical lift, or rotary-wing, technologies could contribute to these planetary science opportunities.

Table 2 – Planetary Science Opportunities (A Partial List Only)

	Science/Exploration Opportunities
Mars	• Search for water or past signs of water (characterize global distribution) • Search for life or evidence of past life • Understand the atmospheric and geological evolution of Mars; perform comparative analyses of the Mars planetary evolutionary process with the other terrestrial-type planets in our solar system • Survey for resources that would expand exploration capability and support for an extended human presence on Mars
Titan	• Search for life or the precursor biochemical components of life • Perform atmospheric science studies to understand the unique nature of the Titan atmosphere (a high density/pressure atmosphere) • Survey for chemical resources/volatiles that could enable in-situ propellant and fuel production at the lander site; propellant could be used for sample return missions to Earth, expanded surveys of the Saturnian moons – including expanded vertical lift planetary aerial vehicle surveys of Titan
Venus	• Correlate space-based cartographic and inferred geological data with detailed surveys in targeted areas using vertical lift PAVs. • Acquire adequate data to understand the fundamental atmospheric and geological evolutionary processes that led our 'sister' planet to be radically different from Earth • Determine if planetary-scale 'green-house' effects can be halted and/or reversed
Jupiter	• Understand the atmospheric science/physics of outer, gas-giant planets • Use outer planet atmospheric data as a comparative benchmark database to refine atmospheric and meteorology modeling – potentially leading to new insights and improvements in meteorology and climatology predictions for Earth • Understand the planetary-scale thermodynamics of outer, gas-giant planets where a net positive heat generation is maintained
Europa	• Search for life or the precursor biochemical components of life • Survey for chemical resources/volatiles for expanded mission/science potential • Acquire data to understand the geophysics underlaying the existence and preservation of a hypothetical Europan sub-surface ocean • Examine fault lines or other potential weaknesses in the ice crust (initially identified from radar-mapping from an orbiter) for siting of 'icebots' and/or other drilling equipment to break through to hypothetical underlying ocean, where possibly 'hydrobots' could be released and explore
The Moon	• Continue to acquire data (particularly through deep-core drilling) to understand the formation process of the Moon • Continue/expand upon search for water ice at the Moon poles; existence of this resource will be critical to the extent and magnitude of lunar exploration • Perform a comprehensive mineralogical survey for the Moon to identify potential resources required for a sustained human presence • Use the Moon as a staging area for continued exploration of the solar system (and through far-side observatories) and the Universe
Asteroids	Perform cartography and geo-chemical analyses to understand planetesimal formation, and, through extrapolation, planetary/solar system formation. • Perform geological and mineralogical survey of asteroids (particularly near-Earth asteroids) and determine if economically valid resources could be extracted from asteroids and transported to Earth or manned space facilities

Table 3 – Contributions of Vertical Lift Technology to Planetary Science

	Potential Vertical Lift Contribution
Venus, Mars, Titan	Vertical lift vehicles (aided by, or solely using, rotors as the means of propulsion) can be developed and flown to support both proof-of-concept, extended robotic science missions, and – in the case of Mars – support human exploration of the planet. Almost all of vertical lift and/or rotary-wing multi-discipline knowledge and technologies would have application to vehicle development and mission execution for planetary science missions to these planets/moons.
Jupiter, Saturn, Uranus, Neptune	Vertical lift capability is not required for any PAVs to be used for scientific investigations of the gas-giant, outer solar system, planets. However, rotary-wing technologies such as rotor aeromechanics (for propeller design), etc., would be applicable for vehicle development for these planets.
Mercury, Pluto, the	The tenuous or nonexistent atmospheres of these planets, moons, and other planetary

Moon, Europa, and other moons, asteroids, and comets	bodies prohibit the application of rotary-wing propulsion. Instead, vehicles employing chemical or electrical propulsion (rockets or ion-engines) will be used for ballistic and/or low-level flight and take-off and landing to explore these planetary bodies. However, even under these circumstances, the rotorcraft and vertical lift technical communities can contribute. In particular, guidance, navigation, and control technologies developed for hover and nap of the earth low-speed flight can still be successfully applied to rocket/ion-engine propulsion vehicles for low-level flight/exploration.

Considerable enthusiasm and support from the American public could be generated for both the demonstration of - and the science returned from - extraterrestrial atmospheric flight.

General Aerodynamic Attributes for Extraterrestrial Aerial Flight

A comparative first-order aerodynamic analysis will now be presented for vertical lift (and other) PAVs. Analysis results for terrestrial aerial vehicles will be used as baselines for the vehicles sized for other planetary bodies. This comparative analysis will be a first step towards understanding the opportunities and challenges of the vertical lift planetary aerial design.

Figures 3 and 4 are approximate estimates of the speed of sound and kinematic viscosity for various different planetary bodies in the solar system. The estimates were made based on data from Table 1, Ref. 1, real gas data from reference 6, and using the Maxwell-Rayleigh power law, $(\mu \sim \mu_0 (T/T_0))^n$, where μ is dynamic viscosity and μ_0, T_0, and n are real gas constants for the primary atmospheric constituent for each of the planets), and the ideal-gas law. Improved thermodynamic equations of state can be used for refined analyses of the atmospheric characteristics of the various planets in the solar system.

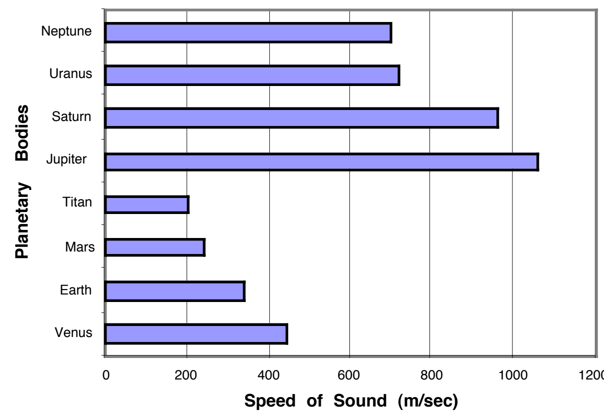

Fig. 3 – Speed of Sound for Different Planetary Atmospheres

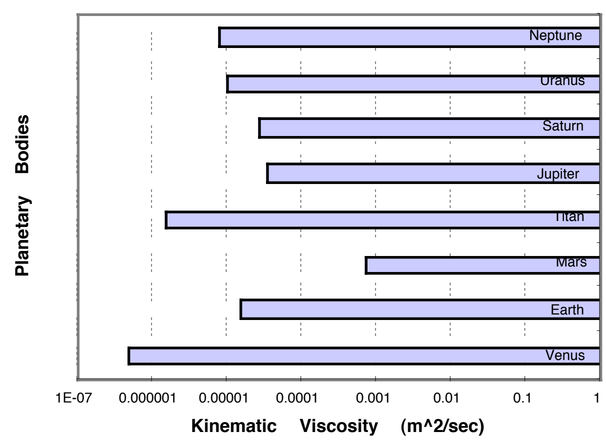

Fig. 4 – Estimates of Kinematic Viscosity for Different Planetary Atmospheres

Figures 5a-d is a set of bar charts for different rotors sized (using simple rotor

momentum theory analysis) for hover in different planetary surface atmospheres, assuming constant solidity (σ=0.1), mean lift coefficient (C_L=0.4), and tip mach number (M_{tip}=0.7). Results for three different vertical lift planetary aerial vehicle masses (10, 25, and 50 kg) are shown in the figures.

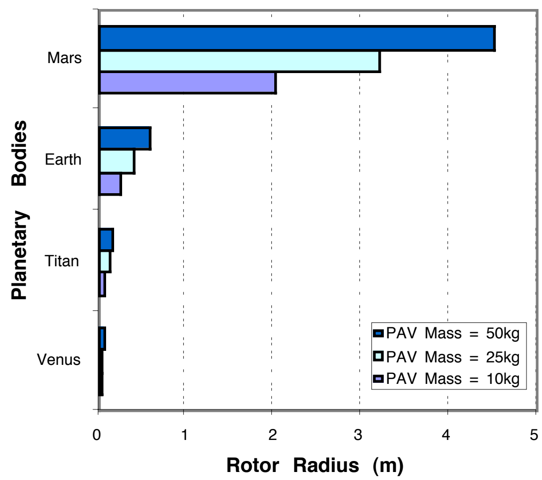

Fig. 5a – Single Main Rotor Radius Sized for Hover

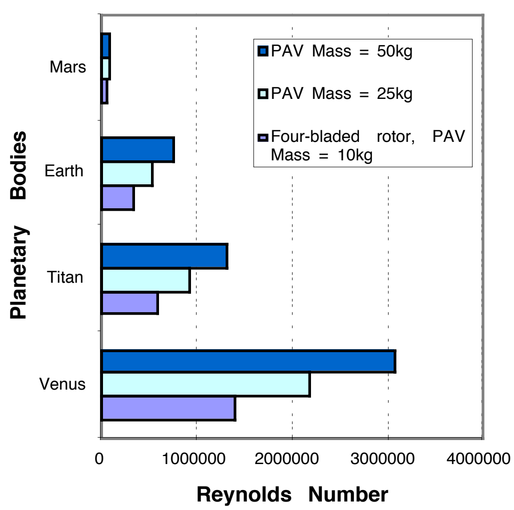

Fig. 5b -- Rotor Blade Tip Reynolds Number

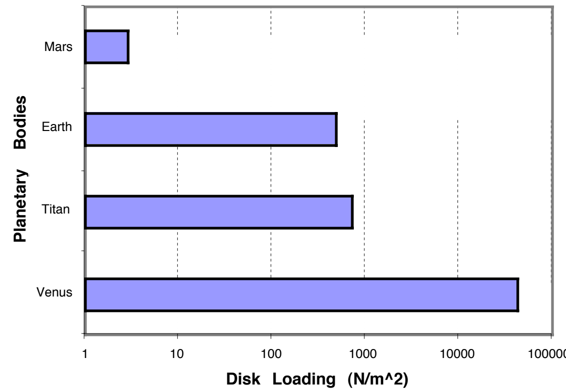

Fig. 5c – Disk Loading of Single Main Rotors

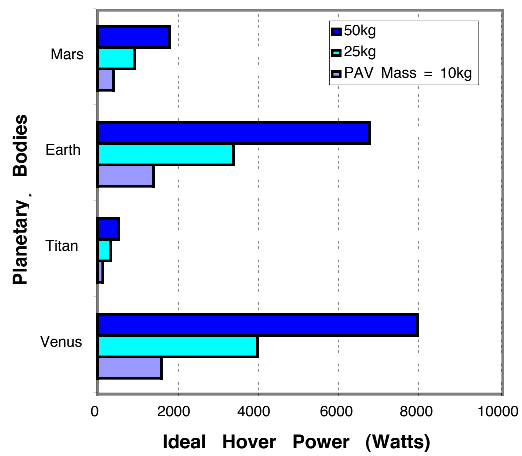

Fig. 5d – Ideal Hover Power of Single Main Rotors in Different Planetary Atmospheres

Figures 5a-d are presented for comparative purposes only; no optimization of the single main rotors has been performed. Figure 5a shows the range of rotor sizes required for hover on each of the four planetary bodies (Mars, Venus, Titan, and Earth) where it might be beneficial to have vertical lift capability. Figure 5b shows the relative extremes of blade tip Reynolds number for rotors on various

planets. Figure 5c shows the range of rotor disk loading for vertical lift PAVs. Figure 5d shows the ideal rotor hover power required.

As shown in Fig. 5c, a rotary-wing vertical lift planetary aerial vehicle for exploration of the Venusian surface would have disk loading approaching that of terrestrial marine screw propellers. Alternatively, a Mars rotor disk loading would be similar to human-powered helicopter rotors (Ref. 7). In both cases, though, no data exist for compressible flow at these density and low Reynolds number ranges. In the case of the Venus rotor, given the unrealistically high disk loading, a tip Mach number of 0.7 is much too high for flight near the surface of Venus. A more realistic tip Mach number range would likely be M_{tip}<0.2. The disk loading for Titan, though high, appears to be reasonable. For both Venus and the Titan, it is likely that ducted, multi-rotor vertical lift vehicles would be the best design configurations to pursue.

Next, consider planetary bodies (particularly the outer, gas-giant planets) where the use of fixed-wing, propeller driven, PAVs to conduct planetary science missions is sensible. Extraterrestrial propeller design can be significantly leveraged by rotary-wing technology and analysis tools. Figures 6a-e compare wing planform area, propeller size, disk loading, and power required for airplane-mode forward-fight cruise in various planetary atmospheres.

For illustrative purposes only, several vehicle design parameters have been fixed with respect to each propeller/planet design point and are not intended to represent optimal values. The key reference parameters and methodologies underlying the sizing exercise of Fig. 6a-e are summarized in Table 4.

Table 4 -- Key Parameters/Methodology for Fixed-Wing PAV Sizing Comparison

Parameter	Sizing Comparison Reference Value/Methodology
V_{min} Mach #	0.1
V_{max} Mach #	0.2
Maximum mean wing lift coefficient	0.8
Maximum mean rotor lift coefficient	0.4
Wing aspect ratio, AR	5 (moderate aspect ratio was selected to reflect the difficulties for wing fold and deployment from atmospheric entry aeroshell)
Induced drag	$C_{Di} = C_L^2/e\pi AR$ where e~1-0.0066•AR for AR<20 (based on linear curve fit of Oswald efficiency factors cited in Ref. 8,9 for straight wings)
Wing Profile Drag	$C_D=C_{Dmin}\bullet(1+C_L^2)$ And $C_{Dmin}=2Cf\bullet(1 + 2(t/c) + 60(t/c)^4)$ Where Reynolds number corrections were made using $C_f=1.328/R_e^{1/2}$ for $R_e<R_{ec}=5\bullet10^5$ or $C_f=0.044/R_e^{1/6}-1700/R_e$ for $R_e>R_{ec}$ Assuming a reference value of t/c=0.12 for the wing airfoil section thickness ratio being used, Ref. 10.
Airframe parasite drag	$f_e=0.0004m^{2/3}$ for a fixed-wing PAV fuselage and $f_e=0.003m^{2/3}$ for a clean helicopter fuselage, where f_e is equivalent flat plate area and m is the vehicle mass (by the method noted in Ref. 10,11, and 12)
Wing Planform	Unswept rectangular wing
Tail download for trimmed flight	10%
Vehicle Cruise Altitude	Low-level flight is assumed where mean surface values (for all the planetary bodies) for pressure, density, viscosity, and speed of sound are used
Propeller/Rotor Power	Estimates made based on method outlined in reference 13

Figure 6a compares fixed-wing planform area for various PAVs in airplane-mode forward-flight cruise. The wing planform area was sized for the design point condition of $C_L = 0.8$ at the V_{min} Mach number = 0.1.

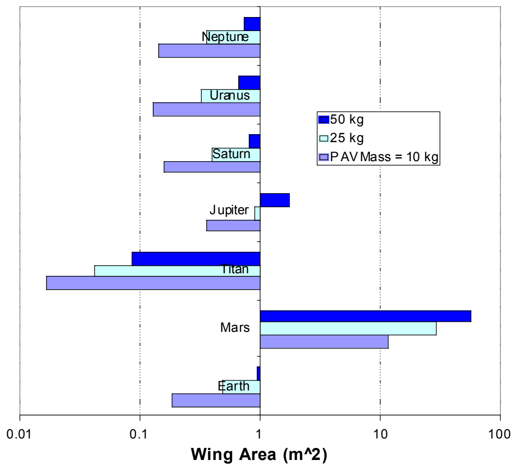

Fig. 6a – Wing Planform Area for Fixed-Wing PAVs for Various Planets

Collectively, PAVs for the outer, gas-giant planets require roughly the same general range of wing planform area. Further, the outer, gas-giant PAVs compare fairly well to the wing area required for equivalent terrestrial fixed-wing aircraft (when sizing is based on vehicle mass, not weight). The Titan and Mars fixed-wing aerial vehicles are at opposite extremes with respect to wing planform area requirements.

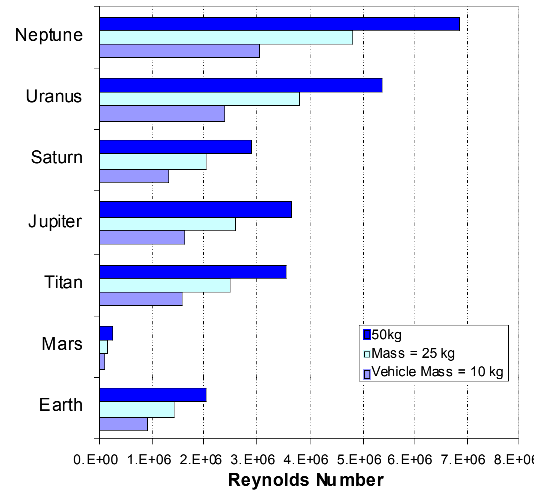

Fig. 6b -- Wing Reynolds Number

Figure 6b shows the wing Reynolds number (based on mean chord length) for the various sized PAVs. Only the Mars PAV clearly has a wing Reynolds number in the laminar flow range. The wing profile drag coefficient is, as a consequence, generally higher for the Mars fixed-wing PAV than for the vehicles sized for the other planetary bodies. The lack of data (particularly for the compressible flow region) for low Reynolds number airfoils, in the range of the Mars PAV airfoils, is one of the design challenges for developing an aerial vehicle for Mars exploration.

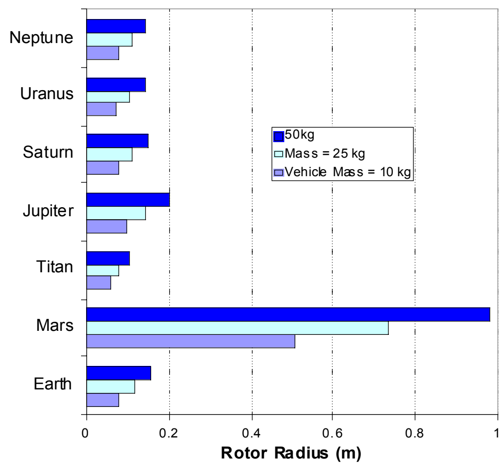

Fig. 6c – Propeller Sizing Comparison for Various Planets

Figure 6c-d compare the rotor radius and disk loading of fixed-wing PAV propellers sized for different planetary atmospheres. Collectively, the terrestrial baseline and the outer, gas-giant planet propellers compare closely to each other in terms of size and disk loading. The Mars fixed-wing PAV propeller is much larger, and has a significantly lower disk loading, than the other vehicles. The propeller/rotor and wing size required for Mars PAVs will pose significant weight and deployment designchallenges.

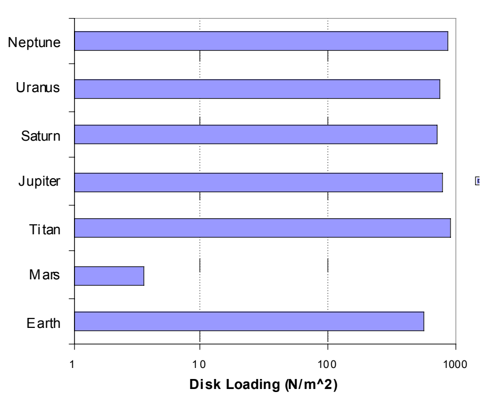

Fig. 6d – Propeller Disk Loading

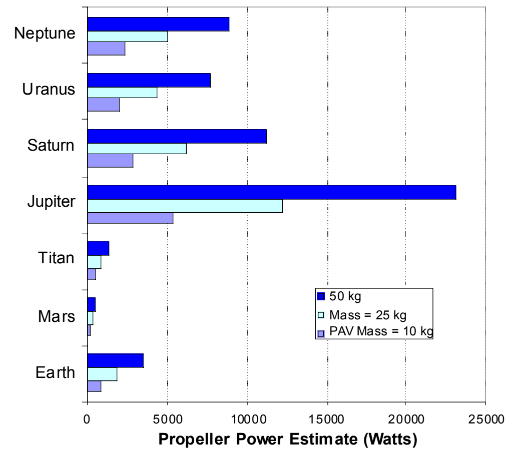

Fig. 6e – Power Estimate for PAV Propellers

Figure 6e compares the propeller shaft power cruise requirements for the various propeller-driven, fixed-wing PAVs. These estimates are based on the methodology of Ref. 13. The Mars and Titan propeller power requirements are much lower than the power requirements for the outer, gas-giant PAVs. Providing adequate power for propulsion for the gas-giant PAVs will be a key design challenge for their development.

A Venus fixed-wing, propeller-driven planetary aerial vehicle is not shown in Fig. 6a-e since the parasite drag will be very large for a Venus PAV that flies close to the planet's surface. Such a vehicle would have to be substantially slower than the other vehicles. (A Venus PAV would have a forward-flight speed of approximately M=0.05 -- versus M=0.2 as assumed for the other vehicles -- in order to have roughly the same overall vehicle drag.)

Vertical lift planetary aerial vehicles do not make sense for gas-giant planets, as

they do not have surfaces to take-off and land from, or hover over, in the conventional sense. Propeller-driven fixed-wing PAVs, on the other hand, do make sense. Because of the high power requirements for higher speeds, the maximum cruise speed has been limited in this sizing comparison to a relatively low Mach number of 0.2. One consequence of limiting the maximum cruise speed to this relatively low Mach number is that the PAV will not be able to make headway against the very strong Jovian (and likely other gas-giant) tailwinds; therefore the vehicle flight-path will be partially dependent upon the upper atmospheric wind-patterns.

A quick review of Fig. 6a-e reveals that vehicles sized for the outer, gas-giant planets will likely look similar to small, moderate aspect ratio, terrestrial fixed-wing unmanned air vehicles (UAVs), with respect to overall propeller size, wing area, and operating Reynolds numbers range. Packaging and deployment of Titan and outer, gas-giant PAVs will be somewhat more tractable than a similar vehicle for Mars – and, yet, power requirements for a Mars PAV will be significantly lower than the other planetary bodies.

Considering more exotic vehicles (from the rotorcraft community perspective), one can envision rotary-wing technologies being applied to other types of planetary aerial vehicles, including hybrid airships (Refs. 14-15) and chemical, or electrical, propulsion ballistic 'hoppers' (Refs. 16-18). Hybrid airships, particularly concepts relying on propellers for not only primary propulsion but low-speed handling/flight as well, can directly benefit from the application of rotary-wing technologies. Even rocket, or ion-engine, ballistic 'hoppers' can benefit from guidance, navigation, and control work developed by the vertical lift and rotorcraft communities. Further autonomous system technology developed for terrestrial vertical lift aircraft can be directly applied to 'hoppers' that would be used for planetary bodies with tenuous or nonexistent atmospheres.

Martian Aviators

As noted earlier, balloons/aerostats (Ref. 19) and Mars Airplanes (Refs. 20-24) have been proposed for some time for Mars exploration. Only recently have vertical lift configurations been considered.

In the near future, vertical lift PAVs will likely focus on Mars - robotic and manned – exploration (fig. 7). This section briefly discusses Mars mission options, and provides some thoughts on a notional early robotic mission.

Assume for the moment a Mars Mission landing date of 2005 or 2007. Assume further that a Martian Autonomous Rotorcraft for Science (MARS) will be deployed from a lander on the surface. The mission for such a Martian autonomous rotorcraft would be threefold: a proof-of-concept demonstration for rotary-wing flight in the Martian atmosphere, a limited aerial survey (with photographic image telemetry) while in flight, and a successful soft-landing on the Martian surface.

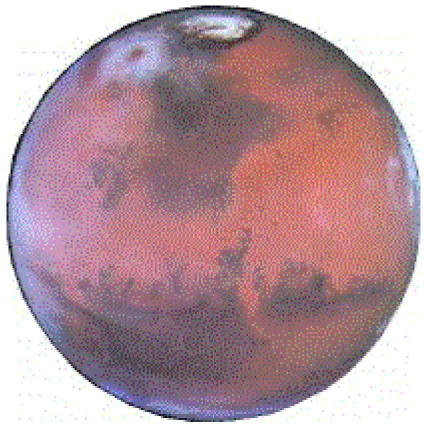

Fig. 7 - Mars

Maximum vehicle mass would be quite small, ~10-20 kg. Minimum sustained controlled-flight duration would be for a short period of time – approximately a minimum of a half-hour flight would likely be required. Range would be of secondary concern. Ideally, range should be greater than 10 km. Maximum cruise altitude would be quite low – approximately 100 to 300 meters. The vehicle would have to be capable of demonstrating vertical lift capability - and, therefore, should be capable of (at minimum) soft-landing on Martian surface after controlled-flight has been demonstrated.

The Martian atmosphere is 95% CO2 with the remaining 5% comprised of N2 and other trace gases (see Table 1). Further, the atmosphere of Mars is extremely cold and thin (approximately 1/100'th of Earth's sea-level atmospheric density). This is roughly equivalent to flying an aerial vehicle at an altitude of 100,000 feet in the Earth's atmosphere. Further, a variation of approximately 20% for density and pressure will be seen on Mars for both changes in surface elevation and planetary atmospheric mass (a consequence of polar CO_2 condensation and sublimation which occurs on a seasonal basis). Given the thin, carbon-dioxide-based Martian atmosphere, developing a rotorcraft design that can fly in that planetary environment will be very challenging. Despite the low density of the Martian atmosphere, rarefaction effects likely need not be considered in Mars PAV aerodynamic analysis for low-level flight for Reynolds numbers $Re>10^4 \cdot M^2$, M being the Mach number (Ref. 10).

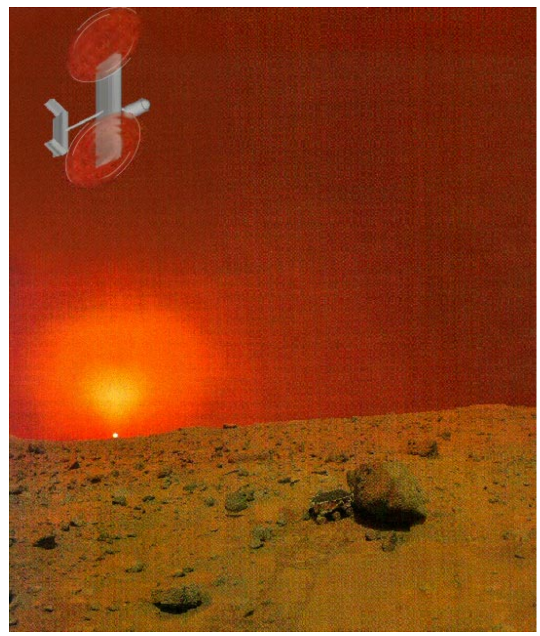

Fig. 8 – Notional Martian Tiltrotor (Some Assembly Required)

A Mars tiltrotor is a particularly attractive configuration option (fig. 8). A tiltrotor represents a good compromise between hover performance and cruise range/endurance – both attributes are extremely important for Mars exploration. Figures 9a-d present some initial sizing/performance estimates for a small (10 kg) autonomous Mars tiltrotor configuration. One of the

biggest issues for the Mars tiltrotor configuration is that the deployment of a tiltrotor from even the surface of Mars will be fairly complicated, and will require astronaut-assisted assembly or an autonomous assembly process on the lander platform.

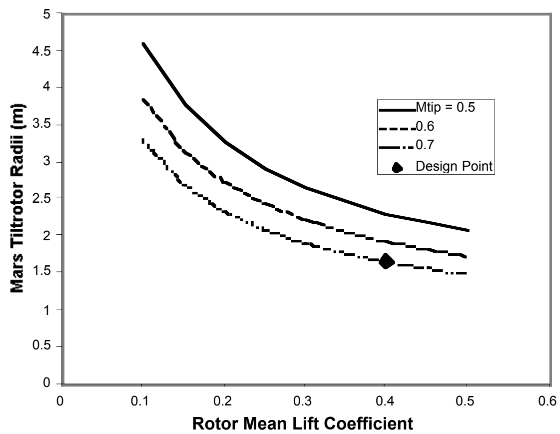

Fig. 9a – Mars Tiltrotor Rotor Radii Size Estimates (Vehicle Mass = 10 kg)

Figure 9a shows the trend of rotor size as a function of rotor mean lift coefficient and tip Mach number. A notional rotor design point of M_{tip} =0.7 and C_L =0.4 is noted on the figure. The resulting rotors are quite large and will necessitate special considerations in stowage (in the aeroshell entry vehicle) and deployment on the Martian surface. This result points to the necessity of folding and/or telescoping rotor blades.

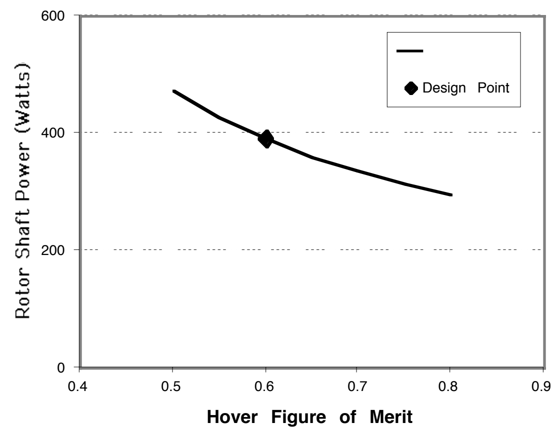

Fig. 9b – Rotor Shaft Power (per rotor)

Figure 9b shows rotor shaft power versus figure of merit (FM). From a practical standpoint, because of the compressible low-Reynolds number regime in which the Mars tiltrotor blades must operate, a low figure of merit was intentionally chosen as a design point (0.6 versus the FM~0.8 noted for terrestrial tiltrotors).

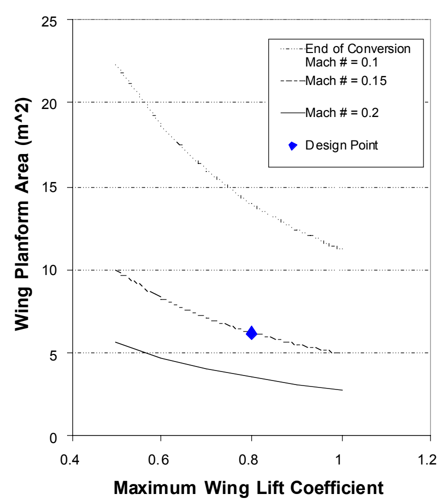

Fig. 9c – Mars Tiltrotor Wing Area Size Estimates (Vehicle Mass = 10 kg)

Figure 9c shows wing planform area as a function of maximum wing lift coefficient and the end of conversion Mach number (airspeed at which the wing, versus the rotors, carries all the vehicle lift). Three considerations constrain the wing sizing effort: first, rotors will have a maximum advance ratio to which the rotors can fly edgewise in helicopter-mode (because of high vibratory loads); second, wing maximum lift coefficient is significantly lower for wing/control surfaces in the low Reynolds number regime; third, aeroelastic stability (particularly for ultra-light weight structures) considerations will limit the maximum cruise speed below that of conventional terrestrial tiltrotors. Unfortunately, it is beyond the scope of this paper to address these design considerations in other than a qualitative sense. The design point noted in Fig. 9c reflects these design considerations/constraints.

Figure 9d shows preliminary range estimates (using the Breguet range equation) of the 10 kg Mars tiltrotor configuration, assuming propulsion provided by an Akkerman hydrazine piston engine (Ref. 25), for various vehicle L/Ds and fuel fractions. The specific fuel consumption (SFC) constant used for the Akkerman hydrazine piston engine is 1.0 kg/MJ. An Akkerman engine is a monopropellent-based propulsion system and, therefore, should operate satisfactorily in the carbon-dioxide-dominated atmosphere of Mars. It has been successfully used on high-altitude, long endurance terrestrial experimental aircraft. A typical L/D for conventional terrestrial tiltrotor aircraft – XV-15 and V-22 – is L/D~7 (Refs. 26-27). Higher L/D values might be possible for an optimized Mars tiltrotor configuration. In particular, lower parasite drag (as compared to terrestrial aircraft) might make it possible to design more efficient Mars tiltrotor configurations.

As shown in figure 9d, a Mars tiltrotor using hydrazine piston engine propulsion will be a short- to medium-range planetary aerial vehicle. In order to improve vehicle range, in addition to improving L/D efficiency of the aircraft, the propulsion system SFC must be improved. This will necessitate developing alternate propulsion systems.

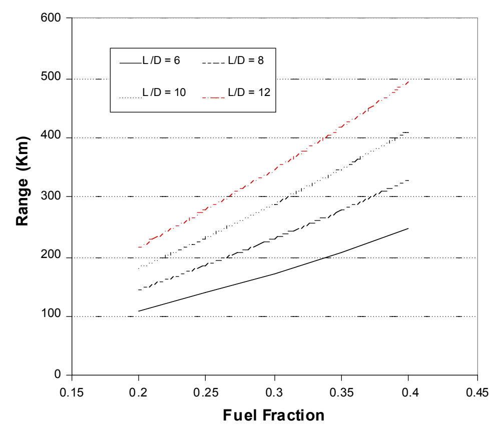

Fig. 9d – Breguet Range Estimates for a Mars Tiltrotor

Throughout this early Mars tiltrotor conceptual/preliminary design work, a one parameter vehicle weight equation was used to estimate the Mars tiltrotor empty weight mass: $m = 0.4 \cdot S^{3/2}$, where S is the wing planform area. This one parameter empty weight equation was derived using empirical tiltrotor and fixed-wing high altitude long endurance (HALE) vehicle weight data. Estimates using this empty weight equation for the 10 kg Mars tiltrotor yield a usable fuel weight fraction of approximately 25%.

Further preliminary design analysis of the Mars tiltrotor concept must be substantiated by detailed component weight estimates.

Another Martian autonomous rotorcraft concept being explored – a configuration more conducive to an early Mission date (because of packaging, assembly, and deployment considerations) – is a coaxial helicopter configuration. This coaxial Martian helicopter should have folded <u>and</u> telescoping rotor blades to minimize volume during launch, transit, and entry/landing on the Martian surface. The primary disadvantage of a coaxial helicopter is that it would be a slower vehicle with considerably less range than a Mars tiltrotor configuration. Nonetheless, a coaxial Mars helicopter would make a good vehicle configuration for early proof-of-concept robotic missions to Mars.

Finally, as a point of reference, the following derivatives are applicable to Mars robotic planetary missions: 1 kg of air vehicle adds 21.5 kg to the lander which adds 13 kg to the entry mass which adds 20 kg to the launch mass. These incremental weight derivatives are derived from the 1998 Mars Pathfinder rover/lander mission (see Fig. 10). The Mars Pathfinder 16 kg rover and auxiliary equipment resulted in 16*(1+21.5+13+20) = 890 kg of launch mass. Mars Mission costs can be approximated using a fixed launch vehicle cost of $70M and an incremental Mission development/flight cost of $180,000 per kg of launch mass (in 1997 USD). Cost numbers based on Mars Pathfinder: $70M plus 890kg*$180,000 per kg = $230M.

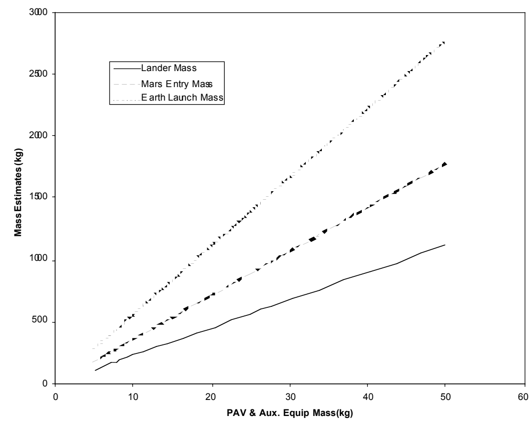

Fig. 10 – Estimates of Lander, Entry, & Launch Mass

Challenges

Autonomous vertical lift PAVs will be high-risk and high-payoff development ventures. Though an impressive – and ever-expanding -- amount of data exists for the planetary bodies in our solar system, nonetheless, these data are barely adequate (at best) for the purposes of designing and building PAVs. Such vehicles will need to be highly adaptive (from a controls and structures perspective), have conservative performance margins, and will require high degrees of mission/flight autonomy to adequately deal with corresponding levels of uncertainty in the mission and flight environment. A list of these and other technical challenges are summarized below.

<u>Rotor Aeromechanics</u>

- Inadequate planetary atmospheric data and/or modeling may exist to design vehicles with required performance.

- No empirical data exist for low-Reynolds number, compressible flow, so aerodynamic predictions may be inaccurate. Correspondingly, no data exist for high tip Mach number, high disk-loading rotor designs required for exploration of Venus and Titan. It is especially critical to acquire airfoil and rotor performance databases consistent with these planetary environment extremes to validate design and analysis tools.
- Achieving aeroelastic stability for rotors and/or wings will be challenging, given ultra-light weight structures required for most PAV configurations.
- A single PAV platform design is unlikely to address all conceivable mission requirements for any one given planet. A mixed fleet of vehicles is likely needed to comprehensive planetary science missions.
- Vertical lift PAVs are not likely to be all-weather vehicles. Season, location, existence of atmospheric disturbances of a certain magnitude, and even time of day may dictate whether a PAV mission can be initiated or not. For example, as noted earlier, Mars undergoes seasonal extremes of atmospheric mass due to sublimation and condensation of CO_2 at the polar caps. Further, seasonal 300-500 km/hr planetary-wide storm fronts (or 'sandstorms' also exist. It is unlikely that PAV missions can be sustained during these seasonal storms. Accordingly, preservation of flight vehicle (and other) assets in the face of these weather extremes will be a key consideration for human exploration of Mars. Further, in the case of Jupiter, retrograde atmospheric wind patterns (on the order of 500-700 km per hour) may dictate the mission profile of any PAV platform used).
- Rotor blade icing will likely take on a whole new meaning for flight on Titan or the outer, gas-giant planets.

Autonomous System Capability

- It is currently beyond the demonstrated autonomous system technology state-of-the art to enable vertical lift flight in an extraterrestrial environment.
- A light-weight, low-power, computationally intensive, reliable (radiation tolerant, for example) flight control and mission computer system capable of meeting vertical lift PAV requirements has yet to be demonstrated. It is crucial to initiate proof-of-concept demonstrations for key hardware/software components for autonomous flight of terrestrial platforms from which vertical lift PAV mission performance can be extrapolated.
- Limited use of lander or orbiter assets should be assumed for guidance, navigation, and control (GNC) and mission/flight support. Onboard-sensors and autonomous system capability should be assumed, although, such complete vehicle system autonomy has not been demonstrated.

Guidance, Navigation, and Control

- Unlike terrestrial UAVs, PAVs can not rely on GPS systems for guidance and navigation (Ref. 28).

- Further, high-precision digital maps will not likely exist for GNC (development of such maps is instead a goal/mission of PAVs).
- Onboard navigation sensors, appropriate for an extraterrestrial environmental for a highly mobile robotic vehicle, have yet to be demonstrated. In particular, planetary atmospheres such as Venus and Titan can be (nearly) opaque to light in the visual range; therefore, non-optical sensors would be required for GNC.
- Exotic (as compared to terrestrial UAVs) types of control actuators or control strategies may need to be developed to minimize vehicle weight, to operate under severe environmental conditions, and to minimize flight control processor workload.

Structures and Materials

- Ultra-light weight structures will be essential for vertical lift PAVs – particularly for Mars exploration.
- Structures and materials will be subjected to incredible extremes of temperature and pressure as well as being subjected to poorly understood levels of atmospheric turbulence, weather conditions, and multi-component and multiphase (and potentially corrosive) chemical constituents.

Propulsion

- Outside of Earth, there is very little free oxygen in other planetary atmospheres. Therefore, new propulsion systems will have to be devised that do not rely on oxygen (or provide for the onboard storage of oxygen that had either pre-launch terrestrial origin or was generated by chemical in-situ production from the lander/mainbase).
- Reliability issues must be taken into account (including auxiliary systems for start/restart) for current implementations of mono-propellant engines such as the Akkerman hydrazine engine (Ref. 25).
- Solar flux availability is greatly diminished for other planets (in the case of Venus because of cloud/haze cover, and in the case of Mars, Titan and the outer planets because of distance from the Sun) for solar energy based propulsion systems. Average Mars solar flux is only ~43 % of Earth's (Ref. 1).
- Nuclear-energy-based (for example, using RTGs (Refs. 29-30)) electric motor propulsion is possible, but a significant weight penalty would be associated with this approach.
- Advanced battery and fuel-cell technology are propulsion system possibilities (Ref. 31), but still need to be matured for space systems.
- For the exploration of outer, gas-giant planets, hydrogen could be drawn in from the planetary atmosphere, compressed, mixed with vehicle-stored oxygen/oxidizer, and ignited in an internal combustion engine.
- Two-stage systems may be a possibility. For example, electric power generation on a lander platform with recharging an onboard battery on the PAV between missions.

Deployment

- PAVs will be subjected to considerable constraints regarding

mass and volume. This will pose challenges for all vehicle development disciplines, but will particularly affect the means and systems involved in the vehicle deployment

- Vehicle assembly, configuring for flight, and deployment of PAVs pose unique challenges compared to terrestrial aerospace vehicles. New design approaches, mechanical systems, and structures will need to be developed for PAVs. The advantage of vertical lift PAVs (over other types of PAVs) is that they can be assembled (if need be), configured for flight, and launched from a lander, with adequate time for deployment; they will not have to rely on deployment during entry into the planet's atmosphere.
- Reelable, foldable, or telescoping variable-diameter rotor blades are all possible candidates for achieving minimum vehicle volume (in stowed/package form) for integration into launch and entry vehicles.

An ambitious undertaking such as the development of PAVs will dictate a whole new design approach that must have a high-degree of flexibility and accuracy to analyze a broad class of vehicle configurations and planetary atmospheric model. Further this design methodology must be predicated on the use of standardized and integrated software packages for preliminary design and analysis, virtual environment, and flight control and autonomous vehicle simulation tools that could be applied to a suite of planetary atmosphere models. The focus of the PAV conceptual design and simulation tools would primarily be on vertical take-off and landing (VTOL) vehicles and hybrid airships for planetary missions.

In order to minimize risk and maximize mission capability and probability of mission success, it will be necessary to develop design and simulation software that will enable rigorous and timely examination of a large conceptual design space for PAVs. As a first step, it will be necessary to adapt existing conventional terrestrial rotorcraft, VTOL, and hybrid airship preliminary design and analysis tools to autonomous planetary aerial vehicle design. In addition, developing specialized tools tailored for PAVs will be necessary, since PAV configurations are likely outside the scope of conventional rotorcraft, VTOL, and hybrid airship empirical data. All analyses will have to draw alternatively on first principles and varying degrees of analysis rigorousness in the iterative design cycle process.

For conventional terrestrial rotorcraft, VTOL, and hybrid airships, mission profiles and flight/operating conditions can be defined in a relatively straightforward manner; this will not be the case for PAVs. Limited, and sometimes only through indirect measurements, data will be available for the planetary environment in which the vehicles will fly, take-off, and land. PAV mission profiles will be partially defined by targets of opportunity identified only during actual vehicle operation/exploration in the planetary environment. Therefore, research will need to be conducted in integrating mission and virtual environment simulation software directly into the design and vehicle simulation software package. Vehicle simulation is only as good as the underlying modeling

employed. Uncertainties in mission definition, planetary environment, and the vehicle design/analysis characteristics could result in inaccurate simulation results and mission feasibility assessments. Acceptable vehicle performance will have to be graded not on the basis of pilot ratings but other mission success criteria.

Unique design constraints exist with respect to the package constraints for the PAV in the aeroshell, the effect on the vehicle due to the harsh environment of space (radiation, vacuum, temperature extremes), and deployment issues from the aeroshell (during descent) or lander (on the planetary surface). Further, considerable work is required to define robust strategies and mechanisms for planetary aerial vehicle deployment, whether it be for: a single integrated atmospheric entry and flight vehicle; PAV high-altitude atmospheric release from an aeroshell; vertical lift PAV deployment from a lander; vertical lift PAV autonomous assembly and deployment from a lander; or astronaut-assisted assembly.

Figure 11 is a flow chart summarizing the preliminary design process that encompasses the multiple disciplines and unique design constraints/considerations of vertical lift PAVs.

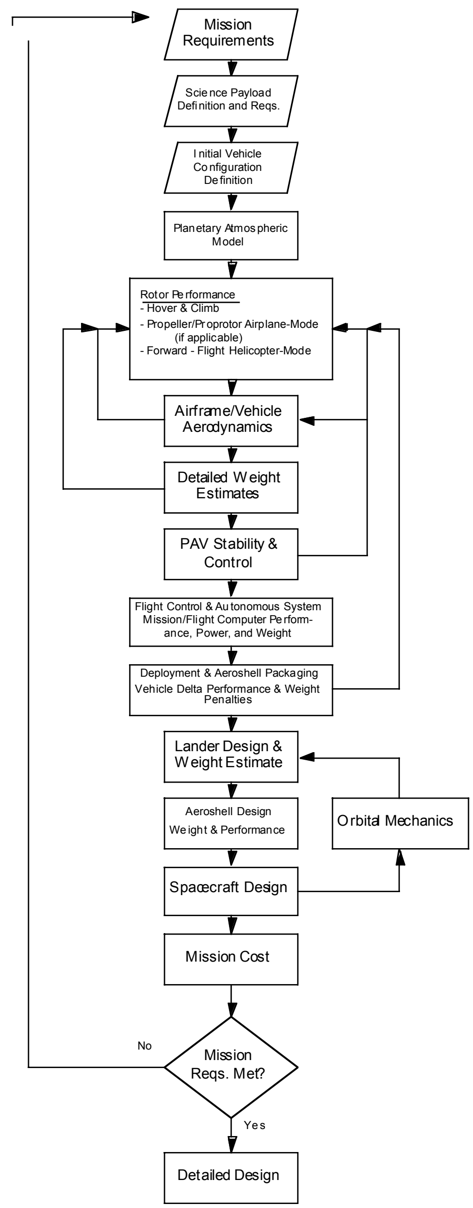

Fig. 11 – Vertical Lift PAV Preliminary Design Cycle

Finally, perhaps the greatest challenge for the aeronautics and rotorcraft communities will be understanding the cultural background and technical requirements of a new type of customer: the planetary science community.

Additional Considerations

In order to maximize the science return from robotic PAVs it may also be necessary to examine and implement the development of hybrid vehicles, symbiotic robotic systems, and/or overall collections or communities of robots and astronauts.

It may be that hybrid vehicles will need to be developed to fully expedite planetary exploration. One such hybrid vehicle may combine flight with surface locomotion capability. Visionaries in the early twentieth century proposed the development of vehicles that combined the features of airplanes and automobiles for terrestrial personal transportation. There may be a greater need to develop such hybrid (flight and surface locomotion) vehicles for extraterrestrial applications. Another hybrid vehicle that might deserve attention from PAVs designers is a vehicle that combines rocket propulsion with rotary-wing lift to optimize overall vehicle performance. Traditional concepts of rocket and aerial propulsion may fall by the way-side by necessity, as will the concepts of independent/separate surface-locomotion and aerial vehicles, for extraterrestrial applications.

Symbiotic vehicles/robotic-systems (for example, a rover transported by and/or linked to a PAV) will likely require development to efficiently expedite planetary exploration. Basically, once a vertical lift planetary aerial vehicle lands it has limited ability (less than a couple of meters at most) to interact with the planetary surface. PAV-mounted robotic arms and similar devices will be insufficient to meet the long-term needs of the planetary scientist. Therefore, symbiotic robotic systems, with either fixed-based or mobile assets with surface locomotion capability, will be an important capability to develop and utilize for planetary science missions. For example, a large, long-range rover could carry a small vertical lift PAV as a scout vehicle to map out both routes and stops for scientific research for the rover. Alternatively, a large vertical lift PAV could sling load transport a small rover, or stationary sensor arrays, to targeted areas of interest. Finally, as a third example, high-altitude, long endurance, fixed-wing (or hybrid airship) PAVs could be linked to vertical lift PAVs to enable/support mission-planning, routing, coordination between multiple vehicles, and extended range communication without having to rely solely on orbiters.

Planetary scientists and computer science and robotics experts are already collaborating to develop collective communities of robots to be used for extended periods of planetary exploration. Of all the planetary bodies in the solar system, the Moon and Mars are unique since one day a sustained human presence will likely be established on them. Robotic systems employing rotary-wing-derived technologies could act as a community of ‘Astronaut Agents’ for efficiently and comprehensively conducting scientific exploration.

Potential for Leveraged, or Spin-Off, Research and Technology

Why is the Army/Rotorcraft Division interested in promoting and participating

in the design study and, perhaps, the ultimate development of vertical lift PAVs? There are several reasons:

- PAV advanced autonomous software/hardware technology is also applicable for terrestrial UAV's;
- Technology developed for PAVs could be applicable to Micro Air Vehicles (MAVs);
- PAV development will promote a strong working relationship between NASA Aeronautics, Space, and Information Technology programs.

Where To Go From Here?

How can the rotorcraft community contribute to the realization of this vision? First of all, the Army/NASA Rotorcraft Division at NASA Ames Research Center intends to continue to sponsor/perform work in the area of vertical lift planetary aerial vehicles. Second, Sikorsky Aircraft is sponsoring the Year 2000 AHS Student Design Competition where the topic is a Martian autonomous rotorcraft. Finally, all other members of the rotorcraft community – both industry and academia – are encouraged to use their imagination and technical expertise to expand upon the vision outlined in this paper.

Concluding Remarks

Autonomous vertical lift PAVs can potentially play a vital future role in the exploration of the solar system. A considerable amount of work lies ahead to establish the feasibility of these vehicles. This paper is just a first step in that overall process.

Specifically, the preliminary discussion and analyses presented in this paper has enabled the following initial conclusions to be drawn:

- Vertical lift planetary aerial vehicles could potentially be developed for Mars, Venus, and Titan;
- Fixed-wing, propeller driven planetary aerial vehicles (leveraging rotary-wing technologies) could potentially be developed not only for Mars, Venus, and Titan but also for the outer, gas-giant planets;
- Finally, even planetary bodies that have tenuous, or nonexistent, atmospheres could benefit from rotary-wing related technologies.

Vertical lift planetary aerial vehicles – if proven to be feasible -- will be employed in both purely robotic missions, or as 'astronaut agents' for manned planetary expeditions. There are, therefore, future opportunities for the rotorcraft and vertical lift technical communities to contribute to NASA solar system exploration initiatives. In the course of developing planetary aerial vehicles, there is considerable spin-off potential to terrestrial rotorcraft.

Acknowledgments

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Aircraft for their efforts on behalf of the AHS International's Student Design Competition on the topic of a Martian Autonomous Rotorcraft for Science (MARS). Finally, thanks in advance should be extended to a future generation of Martian aviators and planetary aerial vehicle designers who will hopefully be inspired to make the vision described in this paper a reality.

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